Broadband RF Transformer Directional Couplers

By Mark McWhorter
Lorch Electronics

Directional couplers play an essential role in the design of radio communication systems. A directional coupler separates and samples signals based on the direction of signal propagation. The engineer uses these devices to unequally split the signal flowing in the mainline and to fully pass the signal flowing in the opposite direction. Well-known published articles describe coupler theory and applications.

Simple and inexpensive to fabricate, VHF- and UHF-band directional couplers are packaged as off-the-shelf items by numerous vendors. Directional couplers, however, can be built from material typically costing one-tenth the price of commercial packages. This article intends to provide theoretical and practical design information to aid the engineer in the expedient and inexpensive fabrication of broadband RF transformer directional couplers for system requirements.

Theoretical Equivalent Circuit Model Analysis

The broadband RF directional coupler shown in Figure 1 depicts two identical transformers wound on magnetically isolated cores represented by primary inductance L_1 and secondary inductance L_2. Port A is driven by voltage V_{in} with a source impedance of Z_o ohms. Ports B, C and D are terminated in Z_b, Z_c and Z_d, respectively (typically 50 ohms each), resulting in the equivalent circuit of Figure 2. The mainline energy path is Port A to Port B. Power from the mainline is coupled to Port D as a function of primary and secondary inductance. Port C is isolated from Port A. Because the coupler exhibits reciprocity, power on the mainline flowing from Port B to Port A will be coupled to Port C, isolating Port D.

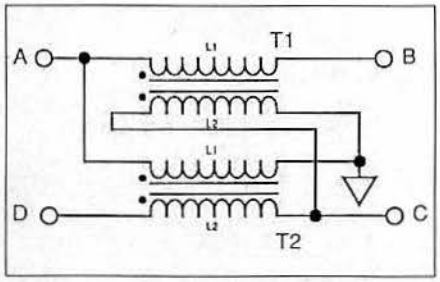


Figure 1. Broadband RF directional coupler.

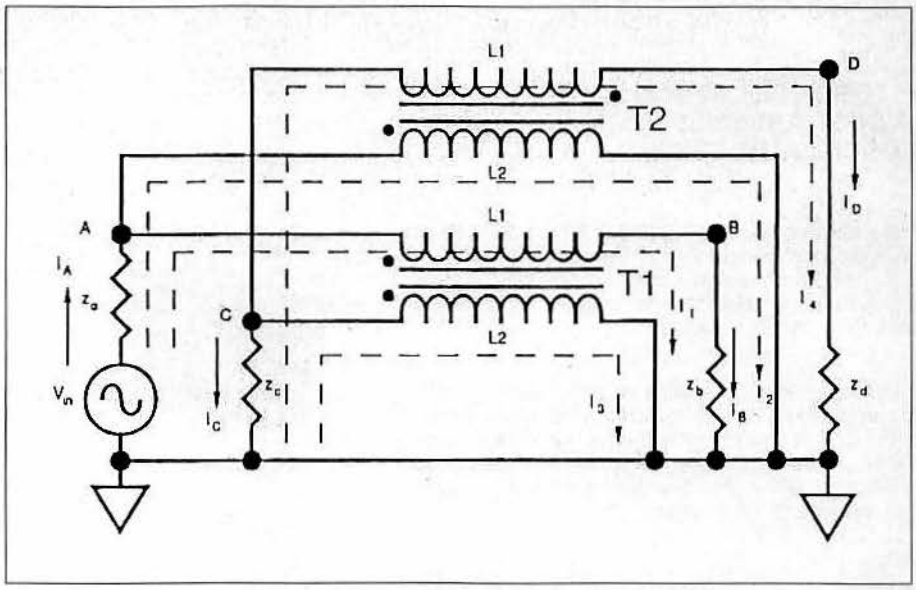


Figure 2. Directional coupler equivalent circuit.

Loop analysis of the equivalent circuit for this four-port device reveals the following set of equations derived from Kirchhoff's Voltage Law, resulting in the matrix equation in the form [Z][I] = [V].

$$\text{Loop 1: } -V_{in} + I_1(Z_b + Z_o + j\omega L_1) + I_2 Z_o + I_3 j\omega M = 0 \quad (1)$$

N	L_2/L_1	Z_a/Z_o	P_{ba}(dB)	P_{da}(dB)	Input VSWR
1	1	0.500	−3.01	−3.01	2.00:1
2	4	0.800	−0.97	−6.99	1.25:1
3	9	0.900	−0.46	−10.00	1.11:1
4	16	0.940	−0.26	−12.30	1.06:1
5	25	0.960	−0.17	−14.10	1.04:1
6	36	0.973	−0.12	−15.70	1.03:1
8	64	0.984	−0.07	−18.30	1.02:1
10	100	0.990	−0.04	−20.00	1.01:1
12	144	0.993	−0.03	−21.60	1.01:1
15	225	0.996	−0.02	−23.50	1.00:1

Table 1. Theoretical coupler performance.

Loop 2: $-V_{in} + I_1Z_o + I_2(Z_o + j\omega L_2) - I_4j\omega M = 0$ (2)

Loop 3: $I_1j\omega M + I_3(Z_c + j\omega L_2) + I_4Z_c = 0$ (3)

Loop 4: $-I_2j\omega M + I_3Z_c + I_4(Z_d + Z_c + j\omega L_1) = 0$ (4)

Inductive coupling between the primary and secondary is related by $M = k\sqrt{L_1L_2}$, where k is defined as the coupling coefficient, possessing a value approaching unity for a well-designed transformer.

Loop currents are found by solving for the matrix [I], and the actual input, output, coupled and isolated port currents are derived from the following relationships:

$I_a = I_1 + I_2$ (Input Port Current) (5)

$I_b = I_1$ (Output Port Current) (6)

$I_c = -(I_3 + I_4)$ (Coupled Port Current) (7)

$I_d = I_4$ (Coupled Port Current) (8)

If the coupler is designed to operate at frequencies such that ωL_2 is orders of magnitude greater than Z_o, k is set to equal 1, and $Z_b = Z_c = Z_d = Z_o$, then the solution for the port currents is reduced to:

$$I_a = \left(\frac{V_{in}}{Z_o}\right)\left(\frac{L_1 + L_2}{L_1 + 2L_2}\right) \quad (9)$$

$$I_b = \left(\frac{V_{in}}{Z_o}\right)\left(\frac{L_2}{L_1 + 2L_2}\right) \quad (10)$$

$$I_c = 0 \quad (11)$$

$$I_d = \left(\frac{V_{in}}{Z_o}\right)\left(\frac{M}{L_1 + 2L_2}\right) \quad (12)$$

Voltage at each port can now be expressed as follows:

$$V_a = \frac{V_{in}L_2}{L_1 + 2L_2} \quad (13)$$

$$V_b = \frac{V_{in}L_2}{L_1 + 2L_2} \quad (14)$$

$$V_c = 0 \quad (15)$$

$$V_d = \frac{V_{in}M}{L_1 + 2L_2} \quad (16)$$

Impedance looking into each port:

$$Z_a = \frac{V_a}{I_a} = Z_o\left(\frac{L_2}{L_1 + L_2}\right) \quad (17)$$

$$Z_b = \frac{V_b}{I_b} = Z_o \quad (18)$$

AT LAST,
ALL TOGETHER, IN ONE HANDY VOLUME THE BEST ARTICLES FROM *RF DESIGN*, ON OSCILLATOR DESIGN.

No more clipping, no more copying, no more scavanging for back issues. No more trying to remember where you read it. This handy booklet contains our best original articles featuring oscillator design...compiled from current issues of RF Design *magazine.*

This complete section of articles will tutor beginners, and keep current designers up to date on the latest techniques. It includes articles that will solve day-to-day design problems...help with analysis and specification...and help even the most skilled engineer improve the efficiencies and versatilities of his designs.

And, best yet, if we receive your order by April 1st, you will receive this softbound booklet for as little as $24.95 per copy. . .**a savings of up to 37%. But you must order today. . .quantities are limited.** *(In a rush? Call our "circulation" department at 303/220-0600, and order today.)*

PRICING:
Quantity 1-9 @ $24.95 each, plus $3.50 total shipping*.
Quantity 10-49 @ $24.95 each, plus $7.00 total shipping*.
Quantity 50-UP @ $24.95 each, plus $12.00 total shipping*.
*NON U.S. ORDERS. PLEASE DOUBLE SHIPPING CHARGE. ALL ORDERS SHIPPED SURFACE MAIL.

---COUPON---COUPON---

RFD 7/91

YES, SHIP ME (QTY) _____ OSCILLATOR BOOKLETS TODAY @ $_____ EACH, PLUS $_____ SHIPPING/HANDLING, **TOTAL ENCLOSED $**_____.

( ) BILL MY COMPANY, SIGNED COMPANY PURCHASE ORDER ENCLOSED.
( ) CHECK ENCLOSED PAYABLE TO *RF DESIGN*
( ) MC ( ) VISA ( ) AMEX EXP. DATE _____
CARD #_____ SIGNATURE _____

SHIP TO:
NAME _____ COMPANY _____
ADDRESS _____ MS _____
CITY _____ STATE _____ ZIP _____
TELEPHONE ( ) _____

MAIL ORDERS TO:
RF DESIGN, 6300 S. SYRACUSE WAY, #650, ENGLEWOOD, CO 80111.

$$Z_d = \frac{V_d}{I_d} = Z_o \quad (19)$$

Power at Port A:

$$P_a = V_a I_a = \left(\frac{V_{in}^2}{Z_o}\right) L_2 \left(\frac{(L_1 + L_2)}{(L_1 + 2L_2)^2}\right) \quad (20)$$

Power leaving the remaining ports:

$$P_b = \frac{V_b^2}{Z_o} = \left(\frac{V_{in}^2}{Z_o}\right)\left(\frac{L_2^2}{(L_1 + 2L_2)^2}\right) \quad (21)$$

$$P_c = 0 \quad (22)$$

$$P_d = \frac{V_d^2}{Z_o} = \left(\frac{V_{in}^2}{Z_o}\right)\left(\frac{L_1 L_2}{(L_1 + 2L_2)^2}\right) \quad (23)$$

The ratio of the power out of Ports B, C and D to the power into Port A:

$$P_{ba} = \frac{L_2}{L_1 + L_2} \quad (24)$$

$$P_{ca} = 0 \quad (25)$$

$$P_{da} = \frac{L_1}{L_1 + L_2} \quad (26)$$

Discussion of Theoretical Circuit Analysis

The preceding equations show that the input port to the coupler will be well-matched when $L_2 >> L_1$. If $L_2 = L_1$, the input impedance drops to one-half the source impedance, resulting in a voltage standing-wave ratio (VSWR) of 2.0:1. The equations also show that Port B and Port D will always be matched to Z_o. With Port A configured as the input, Port B becomes the mainline or thru-path output. Port C is isolated from Port A, and Port D becomes the coupled output.

Equation 26 shows that the system designer is not limited to popular catalog coupling values, but can tailor a device within the practical limits of L_1 and L_2. These equations assume perfect or unity coupling (k=1) between transformer primary and secondary. The inductance ratio between L_1 and L_2 is defined by the turns ratio N, where $N = \sqrt{L_2/L_1}$. Theoretical coupler performance is presented in Table 1. A Touchstone® model using the "XFERP" element was analyzed to further verify this analysis.

Results of Experimental Devices

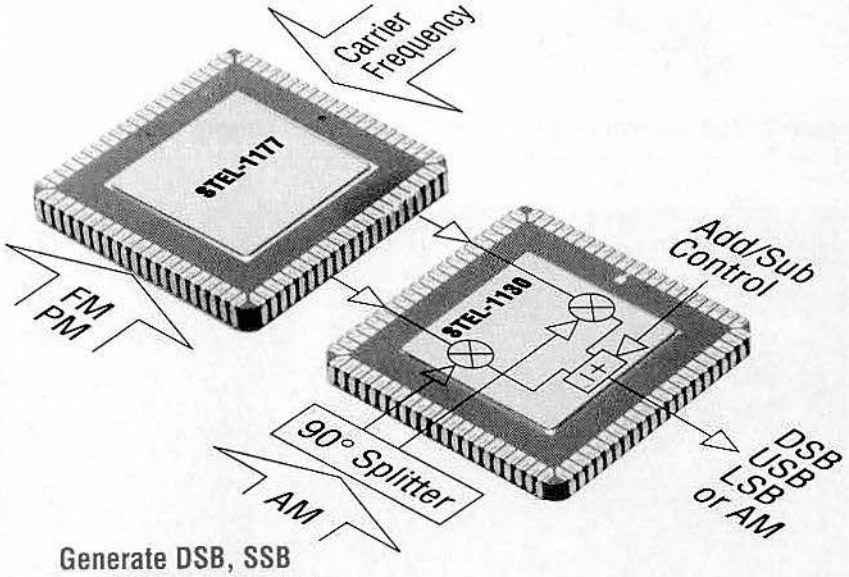
An experimental 10 dB coupler was fabricated using a Siemens B62152-A0008-X030 double-aperture core. Each primary consisted of one turn of #33 Formvar-coated magnet wire. Each secondary consisted of three turns of #38 Formvar-coated magnet wire. A winding diagram and test results are shown in Figure 3 and Figures 4a-d, respectively. This coupler has been used in +31 dBm continuous wave (CW) and 1 percent duty cycle 50W pulsed-power applications with excellent performance in the 10-1000 MHz band.

Additionally, an experimental 20 dB coupler was fabricated using two Mi-

NEW!

The STEL-1130

Quadrature Amplitude Modulator, Dual Multiplier + Adder/Subtractor with 60 MHz Throughput!



Generate DSB, SSB or AM Signals Digitally

The new STEL-1130 QAM chip can be used in conjunction with the STEL-1177 Quadrature FM/PM NCO to generate signals with any modulation format at frequencies up to 25 MHz using Direct Digital Synthesis technology. Linearity of 12 bits for AM and PM and 16 bits for FM is offered.

Typical Applications:

Instrumentation, radio transmitters, modems, and numerous DSP applications including high-speed FFT processors.

ASIC & Custom Products Group
2421 Mission College Blvd.,
Santa Clara, CA 95056
Tel: (408) 980-5684
Fax: (408) 727-1482

STANFORD TELECOM

INFO/CARD 47

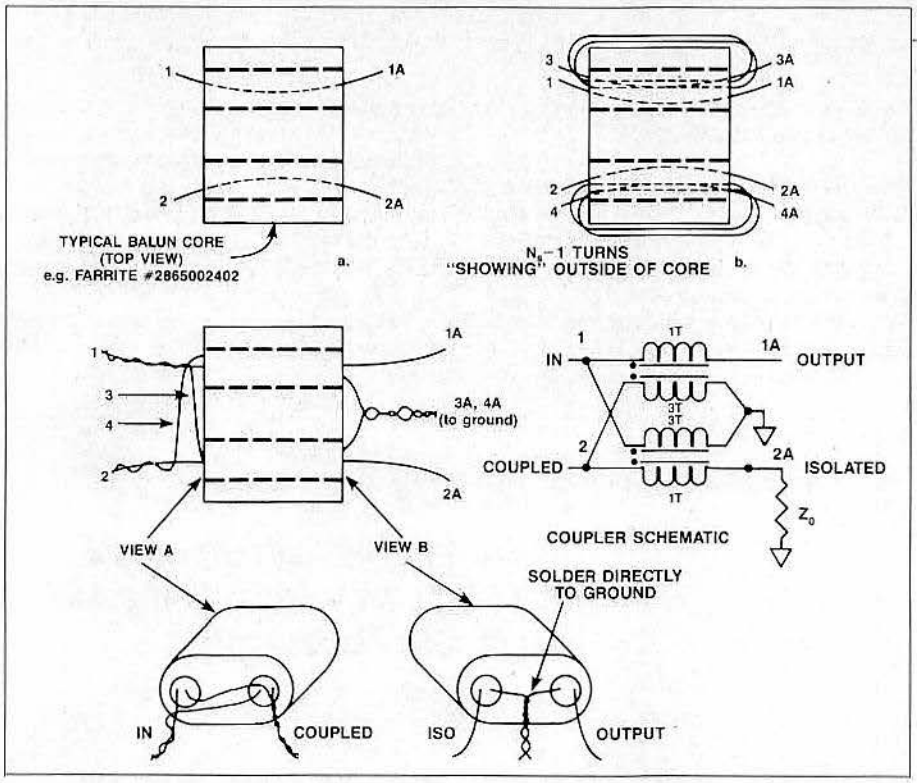


Figure 3. Typical winding for broadband 10 dB coupler at RF.

crometals T25-0 phenolic toroids to investigate high-frequency limitations of the device. Each primary consisted of one turn of #32 silver-coated. Teflon-insulated magnet wire. Each secondary consisted of 10 turns of #36 Formvar-coated magnet wire. This coupler has been used in +36 dBm CW and 1 percent duty cycle 180 W pulsed-power applications with excellent performance in the 500-2200 MHz band.

In general, a coupler can be fabricated using two shield beads, toroids or a single balun core. Low-frequency response is dictated by the ferrite material characteristics and core "form factor." High-end response is partially governed by total wire length, since the core effects are no longer dominant in this frequency range (4). Interwinding capacitance, leakage inductance, copper losses and transformer coupling below unity ($k < 1$) also degrade high-end performance. Properly built devices can achieve good performance exceeding two decades. Power-handling capabilities of 1000 W CW have been reported (3).

F A S T D E L I V E R Y
Fixed Coaxial Attenuators
From cellular to satellite applications, M/A-COM's attenuators cover the performance spectrum.
• dc to 26.5 GHz Operation
• MIL-A-3933 QPL Approved
• All Popular Connector Styles
• Chip Styles: Drop-In Module, Microstrip and Cylindrical
• Power to 20 Watts Avg.
• Precision Calibrated Sets
• Space and Hi-Rel Qualified
• Ultra Miniature (0.75 inch)
• ½ dB Steps to 20 dB and 1 dB Steps to 60 dB
For fast delivery, call our factory or nearest authorized distributor.
M/A-COM Control Components Div.
21 Continental Boulevard
Merrimack, NH 03054-4343
Tel: USA (603)424-4111
UK (0734)580833
Japan 03(226)1671
M/A-COM
INFO/CARD 48

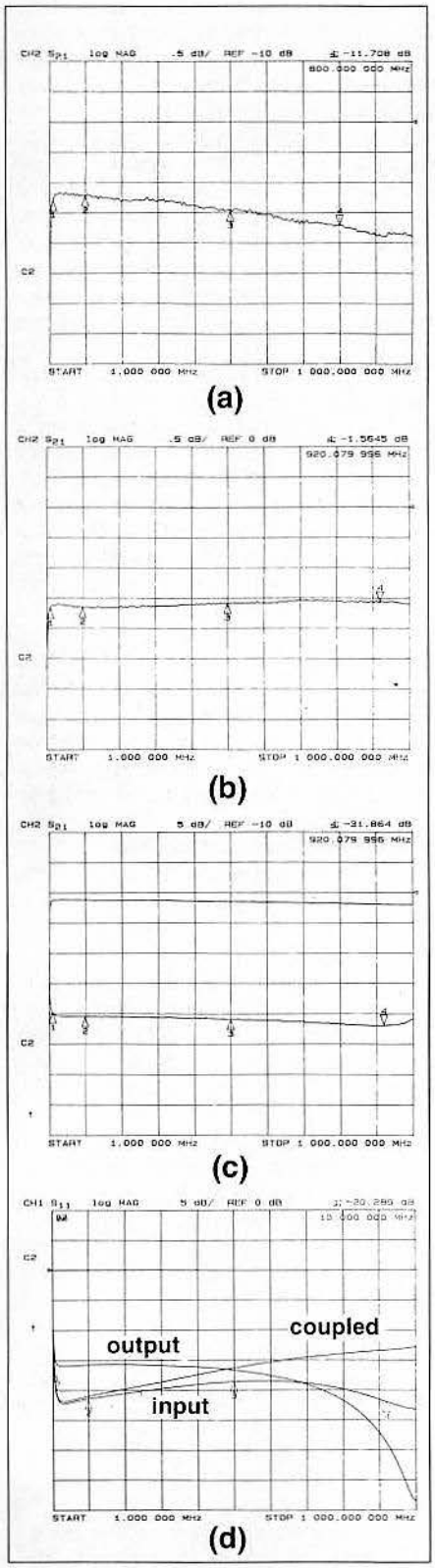


Figure 4. 10 dB coupler prototype, (a) coupling A to D, (b) insertion loss A to B, (c) directivity B to D, (d) return loss.

CRYSTAL FILTERS

• MONOLITHIC • DISCRETE •

TEMEX ELECTRONICS is a manufacturer of Crystal Filters, Discriminators, L/C Filters and Crystals. TEMEX designs to custom specifications as well as the 10.7 MHz and 21.4 MHz standards. We take pride in fast response and the support of our customers. • PHONE • FAX • MAIL •

TEMEX ELECTRONICS, INC.
5021 N. 55th Ave. #10 Glendale, Az. 85301
(Tel) 602-842-0159 (Fax) 602-939-6830

INFO/CARD 49

$8.95* per DDS

* Based on Quantity 1000 of QUALCOMM dual DDS Q2334I-20N.

The best just became less.

Direct Digital Synthesis has never been so affordable! Only with QUALCOMM can you design an advanced synthesizer for under $10 per DDS .

QUALCOMM's dual DDS IC package offers you *two* synthesizers. With two independent DDSs, quadrature channels, timing/clock recovery loops and other applications can be generated from a single IC package.

Even if you require a single DDS output, at $17.90 per package*, QUALCOMM's dual DDS is less expensive than any other single-output DDS available!

Moreover, QUALCOMM's Q2334 full-custom DDS is not a stripped-down synthesizer.

Available in clock frequencies up to 50 MHz, the Q2334 includes 32-bits of phase & frequency resolution, patented Noise Reduction Circuitry to reduce spurs, and full FSK/PSK modes.

QUALCOMM is dedicated to providing you with the highest performance, lowest priced synthesizers available.

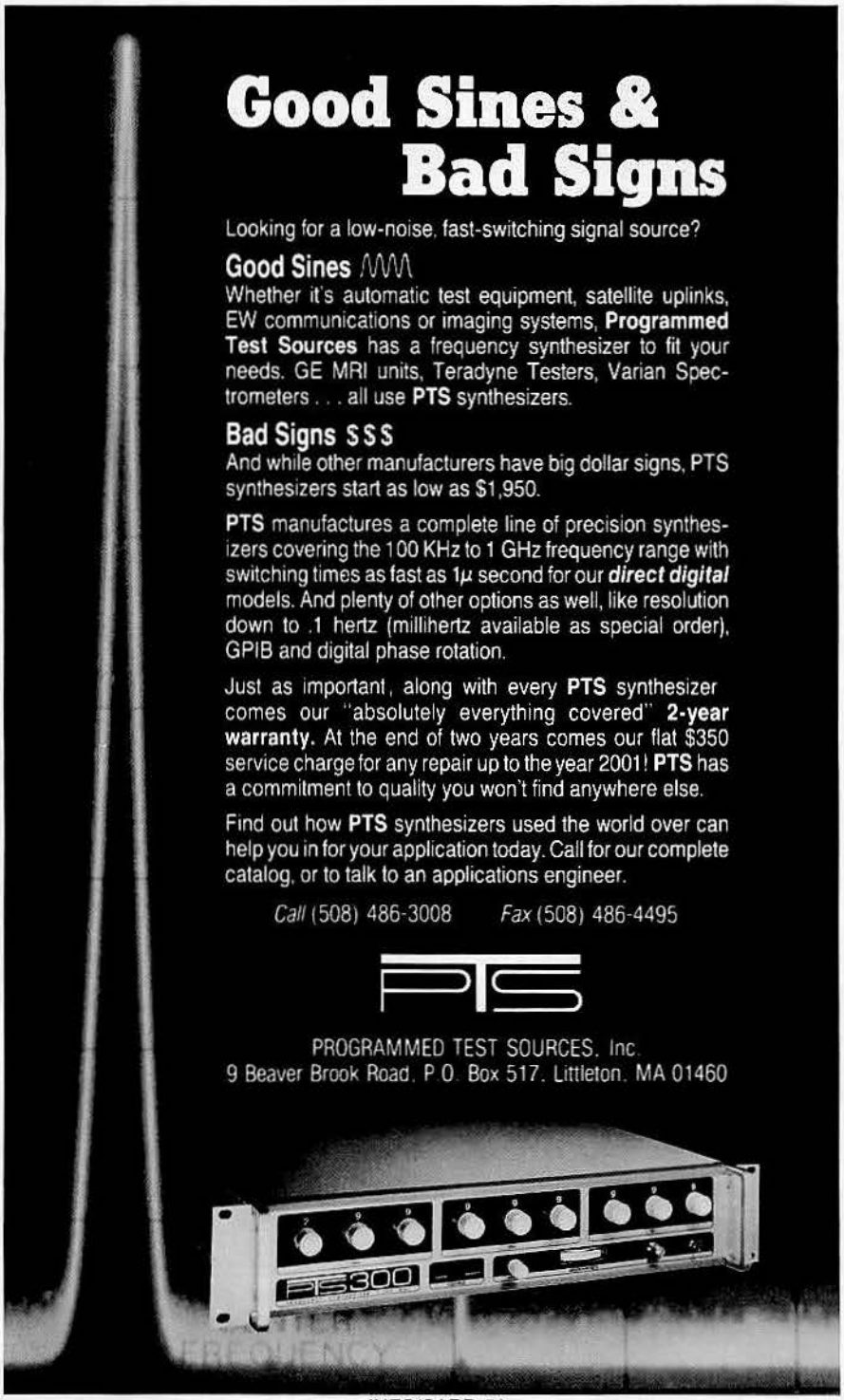
Please call or FAX us for the *new* Q2334 DDS technical data sheet.

QUALCOMM
"the elegant solution"

VLSI Products Division
10555 Sorrento Valley Road
San Diego, CA 92121 USA
TEL: 619-597-5005
FAX: 619-452-9096

INFO/CARD 51

Data shows that the coupler should lie over the ground plane (especially at frequencies exceeding 500 MHz) to help terminate extraneous fields, which degrade loose coupling performance and isolation. Toroidal forms with a relative permeability of one have been shown to perform well for 20 dB couplers in systems exceeding 2000 MHz. Lower frequency devices perform well with initial permeabilities between 300 and 5000. Small shunt capacitance to ground (typically $3Z_o < Z_c < 6Z_o$) at Ports B and/or D can be used to improve match and directivity at the expense of bandwidth. At higher frequencies, lead length must be kept to a minimum to limit parasitic inductance. To achieve broadband performance, ground connection lengths must be minimized.


Good Sines &
Bad Signs
Looking for a low-noise, fast-switching signal source?
Good Sines
Whether it's automatic test equipment, satellite uplinks, EW communications or imaging systems, Programmed Test Sources has a frequency synthesizer to fit your needs. GE MRI units, Teradyne Testers, Varian Spectrometers . . . all use PTS synthesizers.
Bad Signs $$$
And while other manufacturers have big dollar signs, PTS synthesizers start as low as $1,950.
PTS manufactures a complete line of precision synthesizers covering the 100 KHz to 1 GHz frequency range with switching times as fast as 1μ second for our direct digital models. And plenty of other options as well, like resolution down to .1 hertz (millihertz available as special order), GPIB and digital phase rotation.
Just as important, along with every PTS synthesizer comes our "absolutely everything covered" 2-year warranty. At the end of two years comes our flat $350 service charge for any repair up to the year 2001! PTS has a commitment to quality you won't find anywhere else.
Find out how PTS synthesizers used the world over can help you in for your application today. Call for our complete catalog, or to talk to an applications engineer.
Call (508) 486-3008 Fax (508) 486-4495
PTS
PROGRAMMED TEST SOURCES, Inc.
9 Beaver Brook Road, P.O. Box 517, Littleton, MA 01460
PTS300
FREQUENCY
INFO/CARD 50

Increasing the number of turns in the primary is limited by the number of wires that can fit through a small core. Unbalancing the secondaries by adding an additional turn to only one secondary results in a coupling ratio different than those listed in Table 1, without severe directivity degradation. Changing the diameter of the primary wire relative to the secondary wiring changes the coupling by tenths of a dB. Using heavier gauge, Teflon-sleeved, silver-plated magnet wire for the single-turn primaries reduces mainline insertion loss and improves power-handling capability. The isolated port should connect to a good Z_o ohm load impedance, such as a small thick-film chip resistor. A small capacitor, such as an ATC100-series 0.5-2 pF, can be connected in parallel with the resistor to optimize directivity. By eliminating the load resistor, the directional coupler can be used as a four-port, dual-directional coupler.

Conclusion

Directional couplers for broadband VHF/UHF applications are analyzed using transformer theory and can be fabricated quickly and inexpensively. Well-designed directional couplers perform across two decades of bandwidth, and the engineer can fabricate his own device to exact requirements for a wide range of applications. ***RF***

References

1. U.S. Patent Number 3,426,298, "Broadband Directional Coupler."
2. Kuznetsov and Reyushkin, "A Directional Coupler with a Fixed Division Factor," *Elektrosvyaz* (Soviet Union), June 1980, pp. 26-29.
3. McDonald, "Low Cost, Wide Band Dual Directional Coupler," *RF Design*, May/June 1982, pp. 34-36.
4. Pitzalis Jr. and Couse, "Broadband Transformer Design for RF Transistor Power Amplifiers," *ECOM R&D Technical Report*, July 1968.

Acknowledgement

I wish to thank W.G. Beauregard, senior scientist, Olektron Corp., for his sage contribution to my further understanding of these RF devices.

About the Author

Mark McWhorter is the Director of Engineering at Lorch Electronics, a Division of Vernitron Corp. He may be reached at 2801 72nd Street North, St. Petersburg, FL 33710. Tel: (813) 347-2181.